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**OFFICE OF
SYSTEMS**

OFFICE OF MANNED SPACE FLIGHT

Study Report

STUDY OF A MANNED MARS LANDING MISSION USING A MARS ORBIT RENDEZVOUS PROFILE

Addendum B:

Review of Nuclear Propulsion Systems

15 AUGUST 1963

(NASA-CR-64766) STUDY OF A MANNED MARS
LANDING MISSION USING A MARS ORBIT
RENDEZVOUS PROFILE. ADDEDUM B: REVIEW
OF NUCLEAR PROPULSION SYSTEMS (Jet
Propulsion Lab.) 29 p

N74-72684

Unclas
00/99 33685

FACIL

CR 64766
(NASA CR OR TMX OR AD NUMBER)

22
(CATEGORY)

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.**

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Study Report

STUDY OF A MANNED MARS LANDING MISSION USING A MARS ORBIT RENDEZVOUS PROFILE

Addendum B:

[REVIEW OF NUCLEAR PROPULSION SYSTEMS]

OFFICE OF MANNED SPACE FLIGHT (SYSTEM) ADVANCED STUDIES

This report has been prepared by the staff of the California Institute of Technology, Jet Propulsion Laboratory, for Advanced Studies, Office of Manned Space Flight, NASA. The contents of this report reflect the views of the contractor who is responsible for the facts and the accuracies of the data presented herein and do not necessarily reflect the official views or policy of NASA.

15 August 1963

OFFICE OF SYSTEMS
OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C.

U. S. Government

FOREWORD

This study was initiated in order to develop information which would aid the Office of Systems, Office of Manned Space Flight, in selecting the advanced propulsion systems most useful for future manned missions. In the course of the study it became apparent that a decision on the type of advanced propulsion developments necessary for future manned missions could not be made on the basis of this study alone since it was necessary to restrict the breadth of the study to a system performance analysis of a single profile to perform the manned Mars landing mission. The relative cost, schedule, development risk, safety, and probability of mission success of each propulsion system were not quantitatively evaluated; thus the evaluations of these propulsion systems were incomplete, even for the mode considered.

In comparing the performance of the various propulsion systems for the manned Mars landing mission, it became evident that consideration of other future missions could have an important effect on the choice of the advanced propulsion developments to be pursued. It was shown that the relative performance advantage of a particular propulsion system is very dependent on variations in energy and payload weight requirements. Thus a much broader study scope of the manned Mars landing mission and other future missions is required in order to properly evaluate any particular propulsion system.

This addendum is a supplement to the study report entitled "Study of a Manned Mars Landing Mission Using a Mars Orbit Rendezvous Profile". The report was prepared for the Office of Systems by the Systems Support Group as represented by the following members of the staff of the California Institute of Technology, Jet Propulsion Laboratory:

Mr. Dwain F. Spencer
Dr. Marshall E. Alper
Miss Carol L. Funk

Acknowledgement is given to the joint NASA-AEC Space Nuclear Propulsion Office and the Office of Nuclear Systems in the Office of Advanced Research and Technology for contributions to the study of advanced propulsion systems.

Charles W. Cole
Director
Systems Support Group

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ADDENDUM B

REVIEW OF NUCLEAR PROPULSION SYSTEMS

I. INTRODUCTION, CONCLUSIONS, AND RECOMMENDATIONS

This Addendum presents a review of the presently conceived types of nuclear propulsion systems which were considered in the analysis of the manned Mars landing mission. Figure B-1 depicts the various types of advanced propulsion systems in the broad categories of solid-core nuclear propulsion, nuclear-electric propulsion, gaseous-core nuclear propulsion, and other advanced propulsion systems. Of the four categories, the solid-core nuclear and nuclear-electric propulsion systems are the furthest along in development. Since generally there is less familiarity with the advanced concepts, they will be discussed in more detail than the solid-core nuclear and nuclear-electric propulsion systems.

Before discussing the details of each system, it seems appropriate to reiterate some of the conclusions presented in Section III of the main report regarding the use of nuclear propulsion systems and recommendations regarding their development.

1. It appears that properly rated first-generation graphite solid-core nuclear propulsion systems can be used to perform the manned Mars landing mission with spacecraft weights in Earth orbit ranging from 1.0 to 1.7 million pounds, even at the worst oppositions (typically 1979-1980).
2. Development of reactors with power levels of 1,000 and 4,000 megawatts can fulfill the necessary mission requirements if up to four engines can be clustered in any one propulsion module.
3. Maximum burning time requirements for any one engine range from 20 to 25 minutes for initial thrust to weight ratios of 0.3 g's. Also, there is no apparent need for restart capability.
4. Although second-generation solid-nuclear systems may decrease the

required weight in Earth orbit by a factor of 2 or over first-generation solid-core systems, those systems require development of a new reactor technology and advances in structures and cryogenic tankage, and do not decrease significantly the required reactor power levels (2,500, rather than 4,000, Mw) and burning times.

5. Due to the low initial accelerations achievable with electric systems at the expected specific powerplant weights, total trip times using electric propulsion systems are approximately 100 days longer than those with solid-core nuclear systems (even using the latter for Earth escape) for the same weight in Earth orbit. However, the use of electric propulsion systems as ferry support vehicles is quite interesting due to the high fractional payload delivered (1×10^5 lb in Mars orbit, starting with 2.5×10^5 lb in Earth orbit).
6. Due to the high dead weight associated with them, gaseous-core and pulse-nuclear propulsion systems do not offer a weight advantage over staged second-generation solid-core nuclear propulsion systems for the manned Mars landing mission. Their principal values lies in more energetic future missions, especially if continuous propulsion systems cannot be utilized for manned missions which require artificial gravity during flight.
7. Fusion propulsion systems should be capable of performing interplanetary missions ranging from those requiring relatively low energy (typical of the 1971-1972 Mars landing mission) to those with the most difficult requirements, using either a lower weight in Earth orbit or a shorter flight time than any other system.

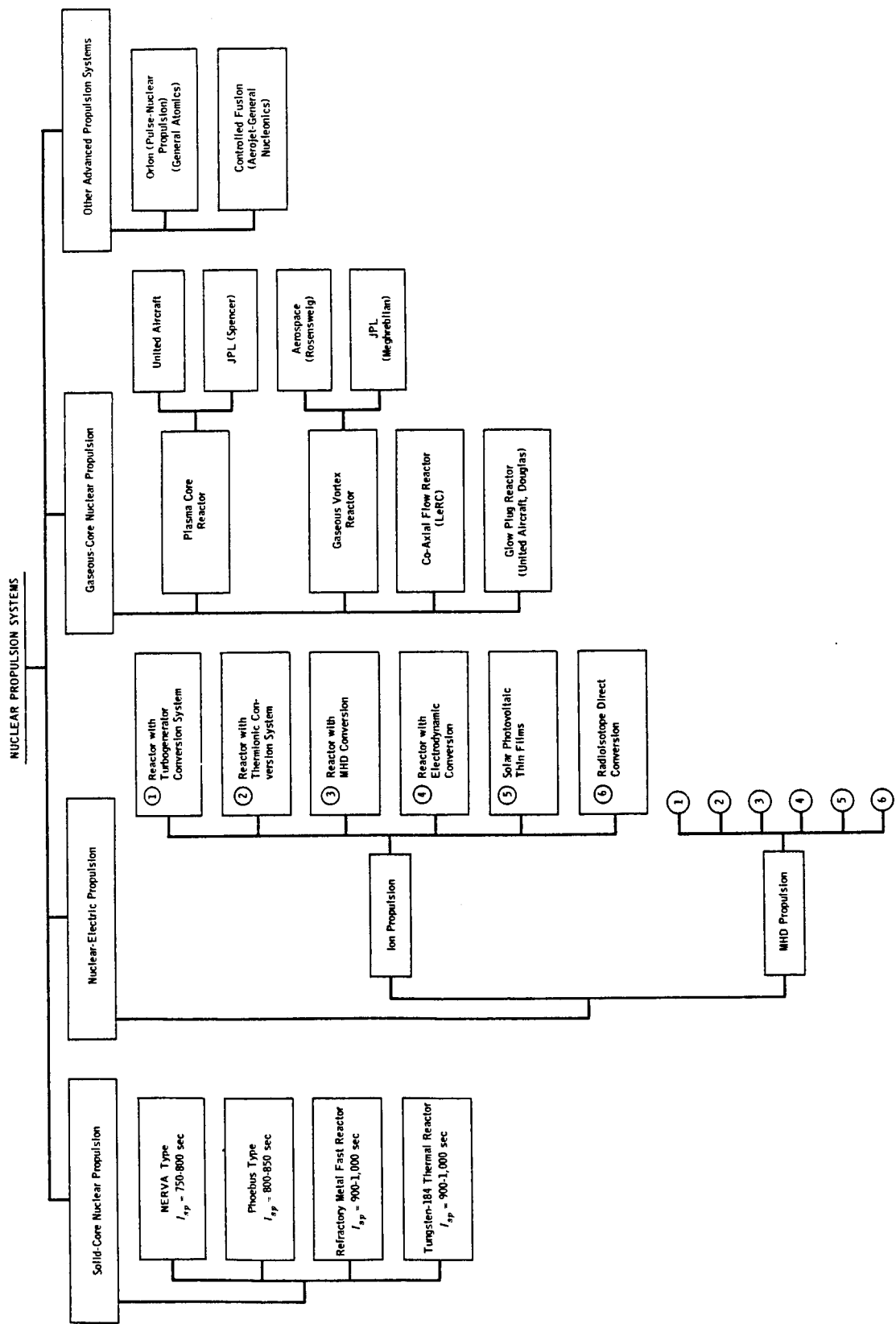


Figure B-1. Nuclear Propulsion Systems

Based on these conclusions, it is recommended that NASA:

1. Continue development of the Nuclear Engine for Rocket Vehicle Application (NERVA) and explore its extension to higher power levels without upgrading performance. Perform extensive testing to insure reliability of the NERVA type of engine and to examine the problems associated with clustering.
2. Develop Reactor in Flight Test (RIFT) nuclear stages on the basis of mission-oriented flight hardware in order to provide a complete nuclear stage test.
3. Devote further study effort immediately to better determine power level and size requirements for NERVA-type graphite engines.
4. Not undertake development of greater performance fast reactor or other new solid-core nuclear engines since the increase in performance does not appear to justify additional expenditures of manpower and dollars.
5. Fortify the Air Force position or provide the required money to perform ground and flight tests of the nuclear pulse vehicle (Orion) to determine whether or not the system

is feasible. The estimated funding required is a total of 20 to 50 million dollars for a 2-yr period.

6. Continue present funding level on research of gaseous-core reactor unless one separation concept is proved feasible.
7. Provide research monies of 10 to 12 million dollars total over the next 4 to 5 years for work on controlled fusion propulsion systems.
8. Perform studies of more advanced manned interplanetary missions to determine the utility of 5, 6, or 7.

Part II of the Addendum reviews the state of the art and problems associated with solid-core nuclear and nuclear-electric propulsion systems. Part III discusses various problem areas associated with the advanced nuclear propulsion systems. Part IV discusses the hazards and contamination problems associated with the advanced nuclear propulsion systems. A discussion of some operational features in the use of the advanced engines is presented in Part V. Part VI considers the expected engine thrust to weight ratios, specific impulse, and dead weights, and the growth potential for the systems, and the performance of the pulse-nuclear (Orion) propulsion systems for the manned Mars landing mission.

II. REVIEW OF SOLID-CORE NUCLEAR AND NUCLEAR-ELECTRIC PROPULSION SYSTEMS

A. SOLID-CORE NUCLEAR PROPULSION

Of the solid-core nuclear propulsion systems, only the NERVA engine is presently under development (by Aerojet-General and Westinghouse Astronuclear Lab under NASA contract. All other solid-core nuclear systems are in the conceptual design and research stages. The NERVA program is an outgrowth of the research performed by Los Alamos Scientific Laboratory of the AEC in the KIWI program.

NERVA is basically an epithermal reactor consisting of an assembly of solid-graphite uranium carbide fuel elements pierced with circular coolant passages. The core proper is surrounded by a beryllium reflector which contains drums of boron strip to provide reactor control. The primary coolant, hydrogen, regeneratively cools the exhaust nozzle, passes upward to provide reflector and control drum cooling, and down through the core before being exhausted. The turbopump is driven with a hot bleed system which taps off propellant upstream of the nozzle.

Each of the core flow channels is orificed to provide equal flow distribution across the core. During startup, the pressure drops across the orifice cause leakage flows along the core periphery. This characteristic is important since it is apparently responsible for the unexpected lateral vibrations which damaged approximately 90% of the fuel elements during the KIWI B-4A test.

One of the principal problems encountered in the KIWI reactor development tests was the combined high-temperature corrosion and erosion of the graphite by hydrogen. Currently, flow channels are lined with niobium carbide (NbC) in order to minimize hydrogen attack. The tests of the KIWI reactors to date have yielded three principal results: (1) the core has nearly a uniform temperature; (2) startup with liquid hydrogen can be accomplished, and steady-state operation presents no control problems; and (3) core support remains the principal problem. The successful startup of the reactor using liquid hydrogen was particularly significant since the core reactivity is very sensitive to the moderating effect of liquid

hydrogen. Should a slug of liquid hydrogen pass through the reflector without vaporizing and reach the core, a rapid increase in power level would ensue, perhaps damaging the reactor.

Substantial effort using component and cold flow tests is now under way to understand the core support and vibration problems. Modification of the seals (orifices) in the leakage flow channels at the core periphery should give a more uniform coolant pressure across the core, thus alleviating the lateral vibration problem. The set of stabilizing slats, exterior to the core proper, has also been modified to provide more effective bundling of the fuel elements. With these changes in design, it is anticipated that the lateral fuel vibration problem, if not eliminated, will be greatly reduced.

The present design parameters of the NERVA engine are given in Table B-I. One of the major development problems is to obtain long burning times. The longest nuclear rocket reactor ground test to date has had approximately a 5-min duration; however, it is expected that the burning time of NERVA can be increased to 20 minutes or even to 1 hour.

TABLE B-I
NERVA Design Parameters

Characteristic	Value
Core length	4.3 ft
Core diameter	3 ft
Power	1120 Mw
Power density	40-50 Mw/ft ³
Exit gas temperature	4,090° R
Chamber pressure	550 psi
Core pressure drop	100 psi
Vacuum thrust	55,600 lb
Vacuum specific impulse	761 sec
Propellant flow rate	73 lb/sec
Burning time	20 min (desired)
Engine weight	14,000 lb

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Startup of the reactor will take place in two phases. The first is a 30-sec period during which the reactor is brought to low power criticality with no propellant flow, and the second, an equal period during which the flow rate is gradually increased to its normal value. At shutdown, cooling must be provided to dissipate the fission product decay heat, or the reactor must be jettisoned. The cooldown will last at least an hour and may be implemented by using continuous or slug propellant flow. The latter method requires a periodic addition of coolant to the reactor to extract the decay heat before the reactor reaches a meltdown condition.

RIFT is the present development program for flight-testing the NERVA engine as a Saturn V third stage. It is being developed by Lockheed under contract to NASA. Currently, such problems as pump inlet conditions under neutron and gamma propellant heating conditions and tank development for systems with combined radiation and cryogenic environments are being investigated. The nominal stage characteristics are a 35-ft-D tank, a 42-ft length, a 25,000-lb stage dead weight, and a 115,000-lb tank capacity.

The present development schedule allows 5 1/2 years between committal of funds and the first flight test. Thus it is expected that the first flights of a hot system will not take place before 1970.

A major problem not evident with chemical propulsion systems is the radiation hazard associated with reactor operation. Ralph Decker of the Space Nuclear Propulsion Office (SNPO) has considered a number of credible accidents possible with a nuclear engine. Two accidents which he considered are a power excursion resulting from the reactor being dropped intact into water (ocean) and a dry excursion due to a malfunction of a control drum. The energy from each of these excursions is 100,000 Mw-sec and 10,000 Mw-sec or a yield of 500 pounds and 3 pounds of TNT equivalent, respectively. These results are to be compared with a total energy release during a normal operating period of 20 minutes of 1 million Mw-sec and the TNT equivalent of the Saturn V propellant alone of 1 million pounds.

For a dry reactor power excursion on the pad, cleanup can begin after 1 day with the facilities at Cape Canaveral, and there is absolutely no problem after 1 week. With the escape of 10% of the fission products, the total iodine dose at Titusville (nearest town) would be 0.3 rad under severe meteorological conditions of no cloud

rise and neutral stability. AEC guides indicate the general public should not receive more than 0.5 rad/yr as a deliberate dose or more than 300 rad from an accident.

To insure against undesired criticality, a shaped charge destruct system which will break up the reactor and a passive poison concept are being studied. The latter approach uses a system of poison stringers which permeate a number of fuel element channels prior to the desired reactor startup time.

There does not appear to be a substantial surface hazard for engine startup in orbits higher than 200 miles. An evaluation of suborbital start systems with ranges sufficient to reach Africa or beyond has not yet been made.

In general, the hazards associated with solid-core nuclear engines should not prohibit their use; however, certain safeguards are required to provide positive protection.

In summary, it appears that reactors of the NERVA type will be flight-tested in the early 1970's. It seems mandatory to perform mission analyses, such as that described in the main body of this report, to determine power levels, sizes, and applicability of systems of this type at an early date. The appropriately sized propulsion systems should be flight tested considerably in advance of mission use in order to establish the reliability required for the manned mission program.

Of the second-generation solid-core nuclear propulsion systems, the graphite reactors (Phoebus) have been investigated in most detail. The object of this work is to increase the reactor power level and power density, operating temperature (higher performance), and engine burning time of graphite reactors. This work is being pursued at Los Alamos.

Fast reactors using refractory metals such as tungsten are being studied at Los Alamos and Argonne. It is hoped to increase the engine specific impulse to the 900- to 1,000-sec range with these systems, while at the same time decreasing reactor weight. Another high-performance, low-weight system, the tungsten-184 thermal reactor, conceived at Lewis Research Center, has been under study by them since 1960. In this concept, tungsten enriched in the low thermal neutron cross-section isotope (tungsten-184, $\sigma = 2$ barns), is used as cladding for UO_2 fuel rods in a thermal reactor. The moderator-reflector (BeO or H_2O) is external to the hot central region, thus allowing lower temperature operation of the moderator than

that possible in graphite engines. The propellant (hydrogen) is first used to cool the moderator and then flows through the hot central region and is exhausted. An advantage of this system over a fast reactor is the simpler control associated with a thermal reactor.

A summary of problem areas associated with the research and development of solid-core nuclear propulsion systems is given in Table B II. The estimates of engine performance characteristics for the systems used in the Mars mission analysis presented in the main body of this Report are based on present predictions. They were broken into reasonable ($l_{sp} = 750$, $\zeta = 0.79$), optimistic ($l_{sp} = 850$, $\zeta = 0.83$) and very optimistic ($l_{sp} = 900$, $\zeta = 0.87$)

estimates for the time period in the late 1970's and early 1980's. (To place these estimates in perspective, the present NERVA engine goals are $l_{sp} = 761$ sec, $\zeta = 0.75$.)

Although it appears reasonable that any of the systems could be developed and available for manned flights in the late 1970's or early 1980's, more extensive manned interplanetary mission studies are needed to determine whether or not second-generation solid-core systems are desirable. At this point, it appears more desirable to develop the graphite reactor technology into reliable nuclear engines than to begin advancement of an entirely new technology.

TABLE B-II
Comparison of Problem Areas
for
Solid-Core Nuclear Propulsion Systems

Description of Problem	NERVA Type (Graphite)	Phoebus Type (Graphite)	Refractory Metal Fast Reactors	Tungsten-184 Thermal Reactor
Compatibility of fuel cladding with hot hydrogen		X	X	X
Enrichment of tungsten-184 isotope for fuel cladding				X
High fuel loadings			X	X
High power density.		X	X	
External moderator (H ₂ O, BeO)				X
Uniformity of thermal neutron flux and propellant temperature in core				X
Sensitivity to liquid hydrogen slug flow	X	X	X	X
Core support and vibration.	X	X	X	X
High nozzle heat-transfer rates.	X	X	X	X
Long burning times.	X	X	X	X
Afterheat problem following shutdown.	X	X	X	X
Prevention of accidental criticality	X	X	X	X

B. NUCLEAR-ELECTRIC PROPULSION

Nuclear-electric propulsion systems can be divided into two major subsystems: first, the reactor and power conversion and conditioning equipment and, second, the thrust device, propellant, and feed system. All electric propulsion

systems depend on a supply of electrical energy from a power source. In most investigations to date, this source has been assumed to be a nuclear reactor since such systems promise to have the lowest specific powerplant

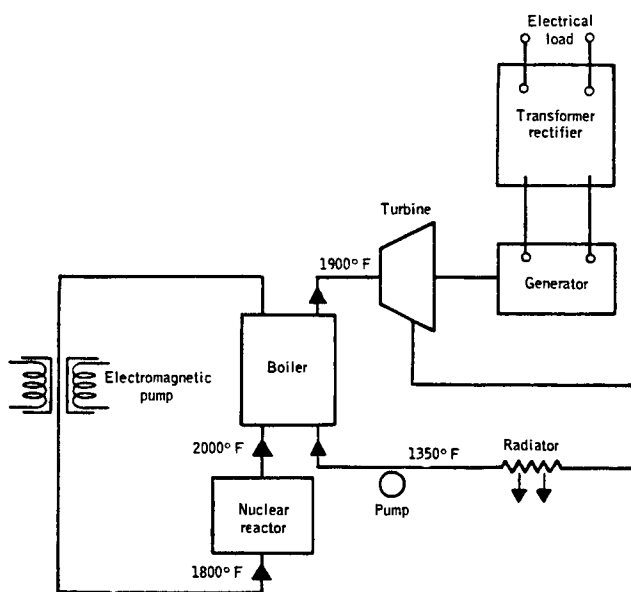


Figure B-2. Nuclear-Turbogenerator Power System

weights (α in lb/kwe) at power levels of interest. There are other possibilities using thin-film solar photovoltaic cells or radioisotope direct conversion, but they are not discussed here. In addition, only turbogenerator and thermionic conversion systems are discussed since these are the furthest advanced, although certain magnetohydrodynamic direct-conversion and electrodynamic conversion schemes appear interesting.

From the mission weight analysis, engine power levels of 5 to 20 Mwe are of interest for electric propulsion of manned or ferry vehicles to Mars. In this power range, nuclear reactor heat sources coupled with Rankine cycle turbogenerator conversion systems or direct conversion (thermionic) systems appear competitive. Presently, the only system under development for power levels in the megawatt range is the Snap 50 reactor-turbogenerator system, a joint AEC-Air Force Program. Although there is no comparable program for a thermionic reactor development, the AEC designation for work on those types is Snap 70. An excellent discussion of nuclear-electric power plants is given in Reference B-1.

For engine powers of 5 to 20 Mwe, reactor powers from 50 to 200 Mwth (approximately 10

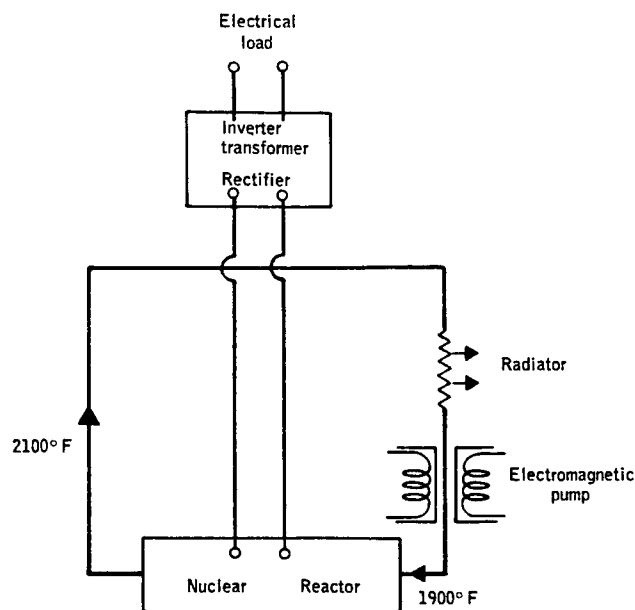


Figure B-3. Nuclear-Thermionic Power System

to 15% over-all conversion efficiency) are required. Fast reactors show promise of providing high-temperature operation for low reactor plus shield weights. This result is basically due to elimination of the moderator, thus decreasing the size of the core and the neutron and gamma radiation shadow shield. A typical fast reactor utilizes UO_2 fueled, niobium clad tubes, and a single-phase primary coolant, e.g., lithium.

In the turbogenerator conversion system (Fig. B-2), the primary coolant transfers the reactor heat to a second liquid metal, e.g., potassium or sodium, in a boiler and is recycled to the reactor. In the simplest design, the secondary or working fluid is then expanded through a turbine, condensed in a space radiator and returned to the boiler. Variations to this require a separate condenser following the turbine to insure working fluid condensation. In this case, a third loop is required to reject the waste heat to space. In general, the optimum waste heat (radiator) temperature is approximately 75% of the turbine inlet temperature.

On the same shaft with the turbine are the alternator and centrifugal pump for the secondary fluid. Due to the sensitivity of the generator stator material and shaft seal to alkali vapor temperature, a separate coolant loop may be

TABLE B-III
Comparison of Problem Areas
for Nuclear Electric Powerplants

Description of Problem	Nuclear-Thermionic System	Nuclear-Turbogenerator System
High reactor fuel temperatures	X	
Foreign materials in reactor	X	
High fuel loadings	X	X
Uniform core power density	X	
Insulation of anode from liquid metal	X	
Insulation and seals between cells	X	
Two-phase loop and zero g condensation		X
Bearing and seal problems		X
Low radiator to peak cycle temperature ratio		X
Low voltage - high current output	X	
Secondary cooling system		X
Long uninterrupted lifetime	X	X

required for generator cooling. The generator electrical output must be transformed and/or rectified to provide the required voltage to the thrust device.

In the nuclear thermionic power systems (Fig. B-3), the fuel elements act as electron emitters (cathodes), and the inner surface of the cooling jacket, as the collectors (anodes) to produce electrical power directly. A gap between the emitter and collector is filled with cesium to reduce space charge effects. The fuel may be unclad (uranium carbide, UC, in a zirconium carbide, ZrC, matrix) or UO₂ clad with tungsten or some other refractory metal. The collector, e.g., Ni, is electrically insulated from the reactor coolant, lithium. The coolant leaves the reactor, rejects the waste heat in the radiator, and is recycled to the reactor. An obvious advantage of these systems lies in the fact that only a single one-phase coolant loop is required and the average radiator temperature is nearly the average coolant temperature in the reactor.

Since each diode produces approximately 1 volt, series-parallel connections are required to obtain the optimum voltage output. For an ion engine requiring an accelerating voltage of 10,000 volts, the optimum reactor output voltage is approximately 100 volts. Thus for a 10-Mwe output, the current rating is 100,000 amps. This power must then be inverted, transformed, and rectified to provide the desired characteristics at the engine. A comparison of the problems associated with nuclear-turbogenerator

and nuclear-thermionic power systems is given in Table B-III.

Of the electric thrust units which have been proposed, the ion engine is the best understood and furthest along in development. Three principal types of ion engines are being developed: the Kauffman - mercury bombardment engine, the Electro-Optical System porous tungsten "button" engine, and the Hughes contact ionization engine.

Basically all ion engines consist of a hot tungsten surface (ionizer) on which the propellant, e.g., cesium, is ionized. The ionized propellant is then accelerated (accel) by a high negative voltage and decelerated (decel) to the desired exhaust velocity. The accel-decel system is used to obtain high current densities of the ionized propellant. The electron which is stripped from the propellant at the ionizer is fed into the exhaust to provide beam neutralization. At one time this was thought to be a major problem; however, vacuum tank tests and three-dimensional analyses indicate that neutralization should be accomplished. Definite assurance will be given only after a space test of an ion engine has been performed.

Since the exhaust velocity of the engine is dependent on the applied voltage, nearly any specific impulse can be obtained. However, the power required to accelerate the ions increases with exhaust velocity; thus there is an optimum specific impulse, depending on the powerplant

specific weight. Specific impulse values of interest range from 5,000 to 20,000 seconds.

The flow rate per unit area or current density of propellant is limited due to space charge effects; thus the engine thrust to weight ratio is also limited. Engine thrust to weight ratios run from 10^{-3} to 10^{-2} g, and engine power efficiencies are approximately 70%. When the entire powerplant weight is included, the thrust to weight ratio is 10^{-4} to 5×10^{-4} g for ion propulsion systems.

It is anticipated that the Hughes and Kauffman engines will be flown on a suborbital test using a battery power supply (SERT — Space Electric Rocket Test) later this year. The thru thrust level for these tests is a few millipounds, and the test duration for each engine is approximately 15 minutes. The principal object of the tests is to assure beam neutralization.

The second type of electric engine which gives promise of specific impulses from 2,000 to 20,000 seconds is the magnetohydrodynamic (MHD) or plasma engine. An important advantage of this type of engine is that the ionized propellant is always in a neutral plasma state, thereby eliminating the need for charge neutralization. In these devices, the propellant is ionized by some means (rf waves, arc sources, etc.) and accelerated either by an external magnetic field or by the self-induced magnetic field from currents in the plasma. There are many variations of the MHD engine, such as traveling wave

accelerators, pulse, systems, etc. Details of those and other systems can be found in References B-2 and B-3. In general, those engines are in the research stage, but should certainly be available by the late 1970's.

Current weight estimates indicate that an over-all system specific weight of from 15 to 20 lb/kwe should be attainable with nuclear-electric systems by 1975 at electrical powers of megawatts. There is a prospect that specific weights may be reduced to 10 lb/kwe, but it is not evident when this can be accomplished. At the present time, it appears that nuclear powerplant development is the pacing item, although problems of engine clustering have not been examined thoroughly.

Mission analyses indicate that a potentially important application of electric propulsion systems may be their use as ferry support vehicles for the manned Mars landing mission. Even in this case, operating times of a year are required to realize the full value of electric systems. Thus a major requirement of those systems is the demonstration of reliable operation for periods of approximately 1 year. For more energetic missions in the solar system, lifetimes upwards of 3 years are required, even for one-way missions. Although electric propulsion systems do not appear particularly attractive for round-trip manned missions, they must be considered further to determine whether or not they should be utilized in a ferry application (see Section IIC in the main body of this Report).

III. REVIEW OF GASEOUS-CORE, PULSE NUCLEAR, AND FUSION PROPULSION SYSTEMS

A. GASEOUS-CORE NUCLEAR PROPULSION

The gaseous-core nuclear propulsion systems have three major categories of problems in common, namely, those associated with separation of the fuel (a fissionable material, such as uranium or plutonium) and the propellant (hydrogen), energy transport from the fissionable material to the propellant, and reactor criticality and control. The principal figure of merit for the system is the so-called separation ratio, which is the weight flow of propellant per pound of fissionable material exhausted. A high separation ratio is desirable from three standpoints: first, to limit the amount of fissionable material used for a particular mission from an economic standpoint; second, to minimize the amount of contamination (fission products) in the exhaust gases; and, finally, to limit the flow of fissionable material to a value which does not compromise engine specific impulse.

To place the economics of these systems in perspective, at the present cost of \$12,000/kg for fissionable material, the loss of 1,000 kilograms of uranium or plutonium during a mission would not be important; but, losses greater than 5,000 to 10,000 kilograms would represent a significant cost.

The total yield of fission products for a typical mission will be 10 to 100 kilotons equivalent, and the hazard associated with this activity must be assessed. Loss of 10,000 kilograms of fissionable material for an entire mission will not significantly affect the engine specific impulse; thus the final point can be ignored in the systems discussed here.

Table B-IV summarizes the various gaseous reactor types which have been proposed and the problems associated with each of them. The problems are classified as those which must be solved for technical feasibility or for engineering feasibility. Basically, the reactor types are delineated by the method used to separate the fuel from the propellant: gaseous vortex injection, the plasma core reactor, the co-axial flow reactor, the combined co-axial flow and vortex reactor, and a glow plug type of reactor. Each of these types is discussed in more detail below.

Generally, the problem in gaseous-core systems resolves itself into maintaining a sufficient quantity of gaseous fissionable material by hydrodynamic or other means to keep the system critical. At the same time, the propellant must absorb the fission energy either by fission fragment heating or by thermal radiation without mixing significantly with the fuel and carrying it out in the exhaust.

Due to the basic physics of the fission reaction, approximately 10% of the energy is released in gammas and neutrons. This energy is not deposited directly in the propellant but is attenuated in the reflector-moderator, thereby limiting the specific impulse of the system to approximately 2,500 to 3,000 seconds. Although it is conceptually possible to increase the propellant specific impulse (exhaust temperature) above these values, it appears that thermal radiation from the propellant to the reflector-moderator will be prohibitive and severely restrict this approach.

With this background regarding the general nature of gaseous reactors, we now consider their progress to date and the most critical phases of the programs. Most of the critical problems are common to all gaseous reactors and are discussed prior to the method of separation.

The measurement of the absorptivity and emissivity of hydrogen from room temperature to temperatures of 10,000 to 15,000°K is probably the most important single experiment. Since the principal mechanism of energy transport from fuel to propellant is by thermal radiation (except in the gaseous vortex), these properties will determine the ultimate performance of gaseous core systems. The absorption spectrum must be that which corresponds to the emission spectra from either uranium or plutonium at their operating temperatures (15,000 to 30,000°K). The first step in a program to obtain this information is underway at the Lewis Research Center. This work will probably extend for 3 to 4 years before complete information is available.

TABLE B-IV
Comparison of Problem Areas for Gaseous-Core Nuclear Propulsion Systems

Description of the Problem	Solution Required for		Gaseous Vortex (JPL & Aerospace)	Plasma Core (JPL & Aerospace)	Co-Axial Flow (LeRC)	Co-Axial Vortex (United Aircraft)	Glow Plug (Douglas & United Aircraft)
	Technical Feasibility	Engineering Feasibility					
Hydrodynamic separation of fuel and propellant.	X		X	X	X	X	X
Solid wall separating fuel and propellant.	X						
High pressure injection (100 atm).	X		X		X	X	
Flow instability (without internal heat) generation.	X		X	X	X	X	
Flow instability (with internal heat) generation.	X		X		X	X	
End wall flows.	X		X				
Achievement of fuel concentration sufficient for criticality	X		X				
Very heterogeneous system requiring high fuel concentrations for criticality		X	X	X	X	X	X
Fission fragment heating of walls	X		X	X	X	X	X
Thermal radiation emission spectra of U and Pu	X		X	X	X	X	X
Absorption of thermal radiation from fuel in propellant	X				X	X	X
Absorption of thermal radiation at walls	X		X	X	X	X	X
Seeding of propellant for energy absorption from fuel	X		X	X	X	X	X
Secondary flows required for cooling		X	X(?)				X
Heavy reflector-moderators for criticality.		X	X	X	X	X	X
Severe stresses in reflector-moderator.	X		X	X	X	X	X
Complex fuel elements.		X	X				
Severe startup problems		X	X	X	X	X	
Nozzle heat transfer		X	X	X	X	X	X
Nonconventional reactor control required.	X		X	X	X	X	X
Significant advances in auxiliary systems (turbopumps, etc.) required		X	X				
Afterheat problem following shutdown		X	X	X	X	X	X
Contamination of atmosphere by exhaust	Not applicable		X	X	X	X	

A second crucial experiment is the room temperature operation of a critical assembly using gaseous fuel and various external moderators. This experiment will determine whether or not present analytical models are sufficient to accurately predict critical fuel concentrations. Neutron source, subcritical, and critical experiments are being planned at Lewis Research Center, and a subcritical experiment is being planned by JPL. These experiments will take from 2 to 4 years, depending on approval and funding.

If these critical experiments are encouraging, a hot critical assembly is necessary before feasibility can be determined. These experiments will include high-temperature startup and steady-state operation of the moderator in a hot reactor. Reactor control has not been considered, in detail, by any group active in gaseous reactor work. Qualitatively, it appears to be a significantly more difficult problem than that experienced with the solid-core nuclear propulsion systems.

The standard procedure in solid-core reactors is to modulate the leakage current of neutrons from the reflector (or moderator, with externally moderated systems). Since the gaseous reactor systems, in general, are quite large due to criticality requirements, large portions of the reflector-moderator must be moved to achieve sufficient control. The mechanisms involved have not been analysed to determine if there is a practical solution.

Such methods as the introduction of boron or some other absorber in the propellant have been suggested. It appears that there is sufficient control potential with boron seeding without a significant loss in performance (reduction of specific impulse by a few per cent). Consideration has not been given control of the boron flow relative to reactivity surges (for example, if more fuel must be fed in instantaneously for some reason). It should be appreciated that these statements regarding reactor control are qualitative and that such control must be examined analytically and/or experimentally.

The hot critical experiments could well require 5 to 10 years, as will their predecessor, KIWI, for the graphite solid-core nuclear systems. Of course, the design of the hot critical assembly presupposes that at least one separation mechanism has been proved feasible during the 2 to 4 years of low-temperature critical experiments.

The final and most crucial requirement, of course, is the evidence of sufficient separation of fuel and propellant to justify engine development. This problem has been the best appreciated and has had the most emphasis in the past. The required value of the separation ratio has decreased from 1,000 to 1 to 30 to 1 basically due to the change in the importance of the costs of the fuel relative to other vehicle costs. Unfortunately, very few significant strides have been made to attain even the 30 to 1 separation ratio.

Experimental and analytical studies have been carried out at Oak Ridge, LeRC, JPL, and Aerospace since 1957 on the vortex reactor. In this approach, a mixture of fuel and propellant is injected tangentially under high pressure into a chamber or tube. The radial pressure gradient provides the mechanism for forcing the light species to the tube center more rapidly than the heavy species, thus providing separation.

Separation of light and heavy species has been exhibited under isothermal conditions, but not to the extent that is necessary to determine feasibility. A critical stage in this research will occur if and when the separation ratio of a vortex system using a light and heavy species with internal heat generation is determined. This test will also determine whether or not it is possible to attain and maintain fuel concentrations sufficient for criticality. These tests should take place within the next 5 years.

A second concept which was explored at JPL and Aerospace from 1960 through 1962 is the plasma core reactor. Here, an external magnetic field was employed to preferentially trap and maintain the fissionable material which has a much lower ionization potential than does hydrogen. Analyses indicated, however, that confinement times were limited to less than a second even if hydromagnetic stability could be obtained. The use of crossed electric and magnetic fields to enhance confinement was considered at Aerospace, but energy requirements to coils appeared prohibitive. There is currently no active work on this concept.

A second version of the plasma core reactor has been studied at JPL since 1961. Here, the external magnetic field is only used initially to trap the fissionable material. Once the fuel is trapped, it would be maintained by injecting the propellant (hydrogen) in a way that provides an axial force counter to the hydrodynamic forces which tend to drag the fissionable material out

the nozzle. Recent cold-flow experimental work indicates that flow instabilities will produce substantial mixing at the fuel-propellant interface, although experiments to measure concentrations of heavy and light species at the exhaust have not been performed. This concept is experimentally behind the vortex work and will continue only at a minimal effort over the next 2 years unless results become more encouraging.

The co-axial flow reactor proposed at LeRC in 1960 utilizes two parallel streams of fuel and propellant. The propellant stream flows at a much higher velocity (approximately 100 to 1) than does the fuel; hence Helmholtz instabilities cause mixing of the two streams. Analytical and experimental programs are underway to determine the magnitude of this effect. Early cold-flow experiments are encouraging, but 2 to 3 years will be required to determine if acceptable separation ratios can be achieved.

Work at United Aircraft on a combined vortex-co-axial flow reactor was initiated in 1961. This concept was designed to utilize the best features of both the vortex and the co-axial flow reactor approaches. It utilizes a very low intensity laminar vortex with provision for end wall and central core flows. Although some significant experimental and analytical work has been performed, experiments using a mixture of a heavy and a light gas have not been especially encouraging. In fact, UAC experiments with helium and iodine show a shorter confinement time than did the constant density, ink in water, experimental results. Estimates of 2 to 4 years,

consistent with the vortex work, are reasonable to determine what separation ratio can be achieved.

The so-called glow plug reactor is a suggestion to utilize a transparent solid wall between the fuel and propellant to maintain separation. There is obviously no fuel loss if the device is successful. The exact emission spectrum of the fuel must be determined, along with the transparency of the solid wall over the band of wave-lengths. Fission fragment heating must be superimposed on this radiation heating to determine whether heating rates are reasonable. In addition, fission fragment impact, along with neutron and gamma interactions, may significantly change the wall optical properties during operation. Minimal effort for the next few years is justified if only because this method does provide "perfect" separation if successful.

Feasibility has not been established for any of the gaseous reactor concepts. It is conceivable that the method of separation which will be most successful has not yet been suggested. Of the systems considered, the co-axial flow and combined co-axial-vortex concepts appear to offer the most promise, although even these concepts have many unanswered problems.

At least 5 years is required to determine the technical feasibility and probably 5 to 10 additional years, the engineering feasibility of these concepts. If engine development could be initiated by 1970, operating engines might be available by 1980 for mission utilization in 1982 or 1983.

B. PULSE NUCLEAR PROPULSION (PROJECT ORION)

Project Orion is the pulse-nuclear propulsion concept originated at Los Alamos and being pursued at General Atomics. Work has been under way since 1957 and has concentrated on specialized technical problems. The pulse-nuclear system has been analyzed in more depth than any of the other advanced nuclear systems and is presently at a stage where nuclear testing is required to determine technical feasibility. The basis for the device is the momentum interchange between a shaped nuclear charge and a pusher plate at discrete times. The principal problems arise from the thermal and momentum transfer during this encounter.

The areas which must be investigated to determine feasibility are listed in Table B-V.

Of these areas, pusher ablation has been the one of principal concern. Experimental work using high-energy explosives with various "propellants" has generated some encouraging, but inconclusive, results regarding the ablation problem. Work on other problems has been primarily confined to paper studies.

Although there are a number of subsystem problems which can be considered analytically and experimentally, the primary question to be answered is that of the pusher interaction using nuclear explosives. General Atomics has proposed certain limited nuclear ground and flight tests to the Air Force to determine whether or not this problem can be handled. The next step in the research necessary to determine system

feasibility is the performance of those tests. They will not guarantee engineering feasibility, but they should establish technical feasibility, if successful.

The tests will require 2 to 3 years to complete. If they are successful, a program for flight testing the engines must be performed. Although some additional ground testing of subsystems can be accomplished, actual flight as an upper stage is required to guarantee system feasibility. This flight testing is required because:

1. Higher-yield bombs than can be conveniently tested in evacuated chambers on the ground are required.
2. Effects of repetitive bursts on the pusher must be determined.
3. Dynamic stability of the vehicle must be ascertained.

These tests will probably require from 5 to 10 years, depending on whether or not early success is achieved. Thus it appears that a development time of 7 to 15 years is required if the system is proved feasible. This requirement indicates the system could be used for late 1970 missions.

If feasible, the use of this system depends, almost entirely, on the philosophy and political implications regarding nuclear detonations in the atmosphere. This problem must be faced and a decision reached relative to the limitations of peaceful uses of nuclear weapons. The recent treaty negotiations between Great Britain, the U.S.S.R., and the United States prohibit all nuclear tests in the atmosphere, including nuclear tests for peaceful applications. It would appear advisable to consider some method of eliminating this block to future effort on the pulse nuclear system since it is apparent that nuclear flight testing is required to determine feasibility of the pulse nuclear system.

TABLE B-V
Problem Areas of the Pulse-Nuclear Propulsion System (Orion)

Description of Problem	Solutions Required for	
	Technical Feasibility	Engineering Feasibility
Shape and expansion of nuclear charge	X	
Propellant type in charge	X	
Ablation of pusher	X	
Structural integrity of pusher		X
Mounting of shock absorber of pusher		X
Shock absorber systems		X
Charge delivery and storage systems		X
Arming device and detonator for charge		X
Vehicle stability and control		X
Misfire		X

C. CONTROLLED FUSION PROPULSION

Controlled fusion propulsion is the least advanced technologically. Controlled thermonuclear (fusion) power has not been demonstrated; however, there are significant differences between a space propulsion system and a land based power plant. Probably most significant is the difference in design philosophy due to weight limitations of the space propulsion system.

A major difference between fusion and fission engines is that there is no separation

problem in the former. The fuel is also the propellant and can be likened, in this respect, to a conventional chemical engine. The most promising fuel for fusion propulsion systems is $\text{He}^3\text{-D}$ since reactions between these two species produce no neutrons (although a certain number will be present due to D-D and D-T reactions). Neutrons are undesirable since they are not affected by the external magnetic field and may deposit their energy in the chamber walls. This energy would then have to be radiated to space by a radiator, thus increasing the powerplant weight.

Use of the $\text{He}^3\text{-D}$ reaction for fusion propulsion systems was suggested at JPL and Aerojet — General Nucleonics in 1960. The latter organization has performed extensive studies of fusion propulsion systems.

The most basic difficulty which must be overcome by either this system or ground-based systems is that of stable plasma confinement. Although the approach proposed by Aerojet to solve this problem is different from many being pursued at AEC laboratories, much of the AEC work is directly applicable to fusion propulsion systems.

The problems which must be solved to prove this system feasible are given in Table B-VI. At this point, the concept is in the basic physics research phase. However, controlled fusion

seems to be easier to implement for space propulsion than for ground-based powerplants since ignition problems are minimized (no pumpdown requirement in space, losses from the magnetic bottle can be used for thrust, and the use of the $\text{He}^3\text{-D}$ reaction, which would be non-economical for land-based powerplants, appears to offer an enhanced possibility of stable confinement).

To place a timetable on the research and development necessary is meaningless. However, controlled fusion propulsion investigations definitely should be pursued because of their significant performance advantage over other systems (see the main body of this Report). A schedule proposed by Aerojet indicates that perhaps 15 years will be required for development, but this schedule depends completely on the ability to attain stable confinement.

TABLE B-VI
Problem Areas of Controlled Fusion Propulsion Systems

Description of Problem	Technical Feasibility	Engineering Feasibility
Stable plasma confinement using $\text{He}^3\text{-D}$	X	
Plasma operation at a β of at least 0.1	X	
Use of superconducting coils over large volumes . .	X	
Injections and trapping of fuel in the cavity	X	
Thrust augmentation	X	
Cryogenic cooling system		X
Restart capability in case of flame-out		X
Bremsstrahlung and cyclotron radiation losses . . .	X	
Leakage rates of fuel from magnetic field at opposite end from thrust augments	X	X

IV. HAZARDS AND CONTAMINATION PROBLEMS

In assessing the possible accidents associated with fission propulsion systems, there appears to be no overriding difference between the large solid-core, gaseous-core, or pulse-nuclear type if all systems are boosted chemically to some altitude before ignition. Should any of the systems be launched from the surface of the Earth, these arguments are not valid.

At least two types of credible accidents can be postulated using the advanced systems: (1) a chemical explosion at the launch site with the attendant spread of fissionable material and (2) immersion of the stage in the ocean, producing a power excursion. The possibility of a nuclear explosion is extremely remote and not deemed a credible accident.

Analyses of chemical explosions of the magnitude considered here indicate that fragments might be spread up to a 1-mi radius about the launch site. It would be this area which would require certain precautions in cleanup since the allowable concentration of uranium or plutonium in the air is very small. The prospect of vaporizing a significant amount of fuel and releasing it to the atmosphere seems remote; however, it should be considered.

The second accident could result if the destruct system failed and the nuclear stage fell intact into the ocean. An actual vehicle would have to be considered in order to assay this danger. Even if the stored fuel should become critical, there would simply be an excursion releasing a significant number of fission products. Analysis of a 1-million-lb thrust solid-core nuclear engine (a thrust level comparable to those envisioned for the advanced systems) indicates that a total energy release of 100,000 mw-sec would result from an excursion. The exclusion area for unshielded personnel from gammas and neutrons is approximately 1 mile, whereas the release of 10% of the fission products requires an exclusion area of 8 to 10 miles under low (worst) wind conditions. Although specific evaluation of the advanced engines must be made to determine their associated hazard, these estimates for the heat exchanger system are indicative of the exclusion area required.

An accident which is peculiar to the pulse-nuclear vehicle stems from a possible misfire. If the charge is dropped but not ignited, what happens as it re-enters the atmosphere? Since the charge is designed for multipoint ignition, it is inconceivable that a nuclear explosion would take place; hence, at most, a chemical detonation would result.

Probably the most important problem which must be faced is that of atmospheric contamination due to fission products in the exhaust gases. It is obvious that a decision regarding United States policy in this regard is necessary before use of these advanced systems is possible.

For a typical high-energy mission, a total of approximately 150 kilotons equivalent yield of fission products is exhausted from a gaseous-core propulsion system (assuming all fission products escape). A comparable pulse-nuclear vehicle releases a total of 1 megaton equivalent yield, or a yield approximately a factor of 10 greater than that from a gaseous-core system. To place these values in perspective, the total yield of the 1962 atmospheric nuclear tests of U.S. produced 37 megatons total yield, of which 16 megatons were fission products. Russian testing in 1962 produced a total estimated yield of 180 megatons, of which 58 megatons were estimated to be fission yield.

Thus, although the release of 1 megaton of fission products is appreciable, it will not significantly change the background rate at the Earth. Even with 100 flights of vehicles of this type, there would be no substantial increase in background; however, the total fission yield would be approximately the same order as that from the U.S. or U.S.S.R. tests in 1962.

It should be noted that many of the fission products will not be trapped near the Earth, but will escape. The fraction of the fission products which are actually retained in the Earth's atmosphere has not been determined. To do this, trapping by the atmosphere and the Earth's magnetic field must be integrated over an actual vehicle trajectory. Regarding the magnetic field trapping, the possibility of producing a low-altitude electron belt from the nuclear pulse vehicle such

as that produced by the recent Johnston Island high-altitude nuclear test must be considered. In that test a total fission yield of 1.5 megatons was released in the atmosphere, and, as is well known, substantial trapping took place. Magnetic trapping of fission products from a gaseous-core system seems remote, since the products will probably be neutral by the time they are exhausted.

If fusion charges are substituted for fission charges in the nuclear pulse vehicle (discussed under growth potential in VI), the atmospheric contamination problems from these devices is nearly eliminated. The only sources of activity would be the fission fragments released from the ignition of the fusion charge (these conceivably could be eliminated if high-explosive chemical ignition of fusion charges is successful) and the carbon-14 activity which is produced from neutron capture in nitrogen-14. The total equivalent yield retained in the atmosphere again must be integrated over an actual vehicle trajectory to determine the amount of atmospheric contamination.

A crucial decision which is required is the attitude that is taken regarding operation of nuclear systems in the vicinity of another planet, such as Mars. If criteria similar to those necessary for operation near the Earth are adopted,

the problem is less severe since the planets are uninhabited. However, if the scientific community requires substantially more restrictive measures, the application and utilization of the full potential of nuclear propulsion systems will be impaired.

To this point, the hazards associated with a controlled fusion engine have not been discussed because they are essentially negligible. There are no fission products from a fusion reaction; thus there is no attendant long-lived activity. There is no "critical" mass, and the system is self-quenching. The principal hazard in a He^3 -D engine is the high neutron flux from the side reactions, D-D (deuterium-deuterium) and D-T (deuterium-tritium). Since the engine is not started up until Earth orbit is attained, and since it has a relatively low thrust-to-weight ratio (10^{-3} to 10^{-2} g), the total atmospheric activation by these neutrons will be negligible, and the only consideration will be that of crew shielding.

In summary, the philosophy regarding tolerable atmospheric contamination will play an important part in determining the use of pulse-nuclear or gaseous-core nuclear propulsion systems. A decision in this regard is as important as determining the technical feasibility of the systems.

V. OPERATION COMPLEXITY AND COMPATIBILITY WITH MISSION UTILIZATION

The operational features of the gaseous-core systems are, in general, complex. In the startup of these systems, the fissionable material must be injected into the cavity and trapped. It appears, for at least two reasons, that pure gaseous (ionized) uranium or plutonium will be used, rather than a halide as has been suggested by some authors in the past. First, the presence of any foreign species in the core will limit the amount of fissionable material that can be trapped, thus making it more difficult to obtain a critical system; and, second, the chemical affinity between halides and hydrogen may produce significant chemical combustion and instability.

In order to minimize the initial transient time to full power operation in gaseous core systems, the fissionable material will probably be injected into the cavity in an ionized state (except in the gaseous vortex system). At the same time, the propellant will be fed under high pressure to the chamber by a separate system. The dynamic relationship of these flows, the temperature transients involved, and the stress conditions in the chamber and nozzle are significant engineering problems which must be considered. The duration of the transient and control during this period pose additional operational problems.

Shutdown of the gaseous-core system appears simpler than that for solid-core nuclear engines since all fission products are exhausted during operation; thus after-heat due to fission product decay is not important. Activation of the structure and/or reflector may still require some coolant flow, but this will be a small fraction of the total flow required during full-power operation.

Steady-state operation of gaseous-core powerplants is similar to that of the solid-core nuclear propulsion systems. System problems include: (1) hydrogen storage, (2) propellant heating by neutrons and gammas, and (3) crew shielding from the reactor environment.

One of the greatest advantages of a pulse-nuclear system is its relative operational simplicity. In essence, the operational sequence is independent of time, except at the end of a series of bursts. A typical operational sequence includes (1) expelling a nuclear charge through a

tube which penetrates the pusher plate, (2) arming and detonating the charge at a specified distance from the vehicle, (3) absorbing the impulse in the pusher plate and shock absorber system and finally the entire vehicle.

As long as the system is capable of taking a certain number of impulses, there is no restart problem since each event is similar to the preceding one. At shutdown or in the event of a misfire, the system experiences an acceleration reversal corresponding to twice the peak acceleration of the vehicle due to rebound from the shock absorber system. This reversal may be the dominant design criterion for limiting pulse vehicle accelerations for manned systems.

Since the fuel is stored in the form of solid charges, there is no fuel storage problem with this system. With the larger systems (greater than 1,000 tons) the pusher plate and shock absorber masses provide sufficient shielding from the nuclear burst; thus the need for additional shielding (except perhaps from solar flares) is eliminated. In general, it can be stated that utilization of the pulse-nuclear system appears much simpler than use of the gaseous-core systems.

The controlled fusion system for space propulsion, like the gaseous-core engines, is quite complex operationally. At startup, a complex ignition sequence is necessary to obtain the required fuel concentration in the chamber. To do this, injection of an excited atomic species into a high-intensity magnetic field will probably be required. A fraction of these particles sufficient for a power balance must be trapped and maintained long enough to get the required fuel burnup. This operation is carried out while the spacecraft is in Earth orbit. Under normal operating conditions, the system is run continuously; however, in case of flame-out, a spare ignition system must be carried to provide restart capability.

The engine requires a separate cryogenic cooling system for the superconducting coils, a refrigeration cycle, and the associated space radiator. The cooling system will probably use helium; hence boiloff and leakage will be important considerations. A separate flow system is required for the thrust augmentor which adds cold propellant to the flow leaving the reaction

chamber in order to increase the engine thrust to weight ratio.

An advantage arises from the fact that the primary radiation source is neutrons. Analysis must be made of structural activation by these neutrons and the attendant crew shielding problems; however, since the power requirements are less than those for the gaseous-core or pulse-nuclear system (lower thrust to weight ratio), shield weights should be low.

If it is determined that manned systems must have artificial gravity fields of at least 0.1 g, any continuous-thrust system such as the low-thrust gaseous vortex, electric propulsion,

or the controlled fusion systems will provide additional inflight stability and control problems. These problems will arise due to precession and nutation from thrust vector misalignment or non-axial thrust direction used for pitch or yaw control purposes.

As is obvious from the examples stated above, there are many operational features of the systems which must be considered prior to a final selection of the propulsion system for an advanced mission. These problems must be weighed carefully in order to choose the propulsion system which best satisfies an over-all program.

VI. ENGINE PERFORMANCE AND GROWTH POTENTIAL

As has been discussed previously, gaseous-core propulsion systems are limited in specific impulse due to neutron and gamma heating of the reflector-moderator. Although it is theoretically possible to remove this restriction by utilizing a secondary cooling system, it appears that thermal radiation from the propellant to the reflector-moderator will be prohibitive. Thus it appears that gaseous-core systems will be limited to approximately 3,000 seconds of specific impulse.

The thrust to weight ratio, however, presents a different view. If these systems can be built, it appears that nearly any desirable thrust to weight ratio can be attained if a very high power level is used ($> 2 \times 10^5$ Mw). Basically, this condition results from the fact that the moderator-reflector weight does not increase nearly as rapidly as does the thrust level for the larger systems. However, the minimum moderator-reflector weight appears to be 0.5 to 1.0 million pounds, depending on the difficulty of maintaining high fuel concentrations in the cavity; thus the engine thrust to weight ratio is least for low-performance applications. The engine power level is limited by the amount of fissionable material which is utilized for a particular mission. As the engine power level is increased, higher propellant flow rates are required, and, for a given separation ratio, higher fuel expenditures result.

The performance characteristics of the pulse-nuclear propulsion system have been obtained from General Atomics. For systems with initial weights from 1,000 to 2,000 tons the expected specific impulse is 3,000 seconds with a dead weight fraction of initial weight of 0.30.

Figures B-4 through B-11 present the required weight in Earth orbit for a vehicle using a single-stage pulse-nuclear propulsion system to perform the manned Mars landing mission. The curves assume a Mars circular orbit rendezvous mode and are presented for superparabolic and parabolic Earth entry using nominal and twice-nominal payload module weights. The

relatively small, $\approx 25\%$, increase in required weight in Earth orbit when the payload module weights are doubled is characteristic of the performance potential of the pulse-nuclear system.

An important advantage associated with the pulse-nuclear system is its apparent growth potential. The anticipated effective specific impulse would be 4,500 seconds for a 4,800-ton vehicle with only slight increases in dead weight fraction ($W_F/W_O = 0.33$ to 0.35). Although these sizes are beyond presently conceived mission requirements, they certainly provide an added incentive for the development of this type of system.

An additional feature of these larger systems is that there is no need for additional crew shielding from the nuclear burst since the nuclear charge size does not increase substantially over that required for the smaller vehicles. At the same time, the mass of the pusher and other systems becomes larger (to withstand the higher temperatures necessary to achieve the higher specific impulse), thus providing a larger effective shield mass between crew and burst.

A final growth factor of importance is the possibility of replacing the fission charge with a fusion charge. Theoretically, the fission product problem can be completely eliminated; but, even if this is impossible at the charge sizes of interest, it should be possible to significantly decrease the fission product yield. In general, one can state that the pulse-nuclear propulsion system shows significantly greater growth potential than do the gaseous-core propulsion systems.

Anticipating increases in performance for the controlled fusion system is difficult since the achievable performance is so uncertain. It is theoretically possible to obtain specific weights of 1 lb/kw or less for this system; however, the estimates given previously in the body of the Report use a more conservative figure of 3 lb/kw although it is by no means certain that even that performance can be achieved.

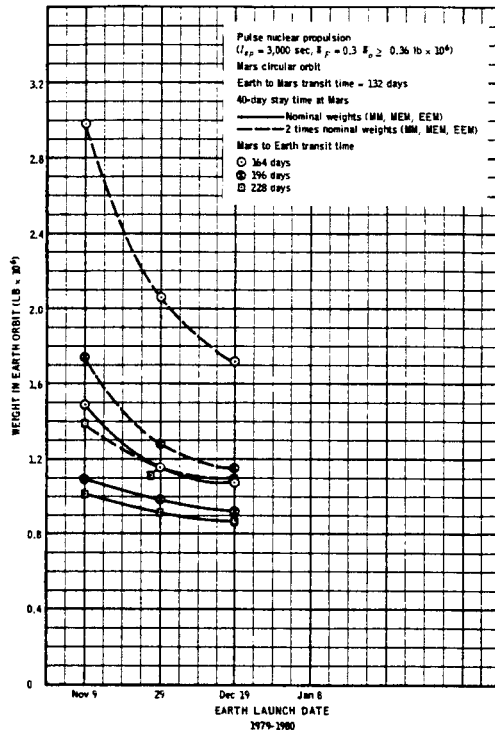


Figure B-4. Weight in Earth Orbit for Manned Mars Landing Mission in 1979-1980
 Earth to Mars Transit Time = 132 Days

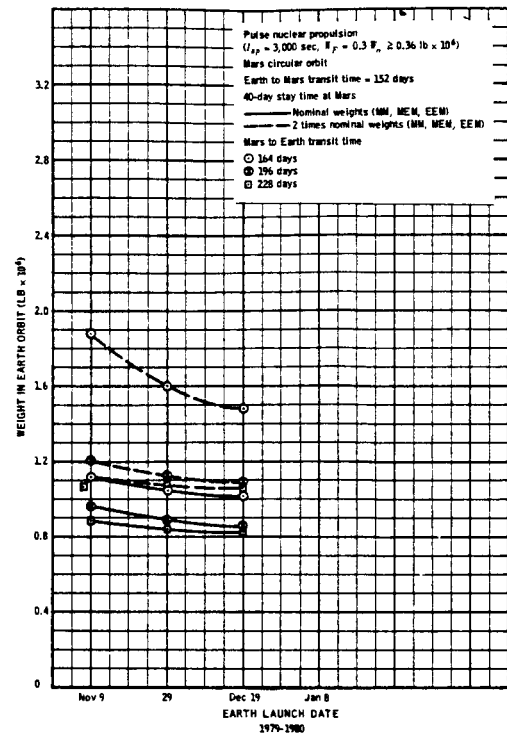


Figure B-5. Weight in Earth Orbit for Manned Mars Landing Mission in 1979-1980
 Earth to Mars Transit Time = 152 Days

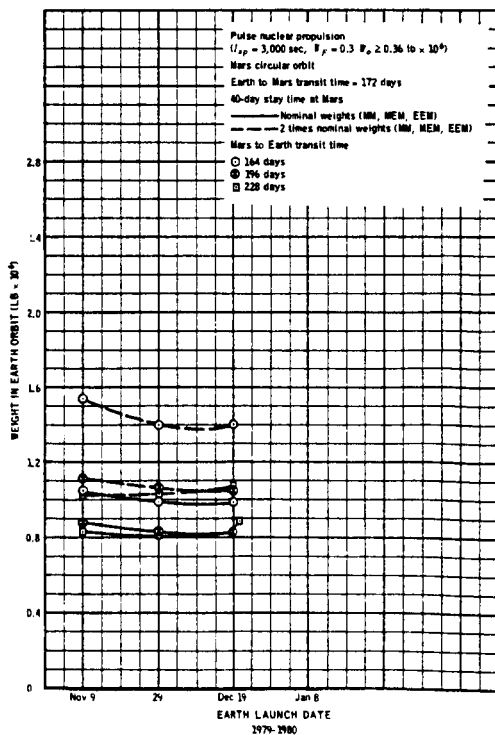


Figure B-6. Weight in Earth Orbit for Manned Mars Landing Mission in 1979-1980
 Earth to Mars Transit Time = 172 Days

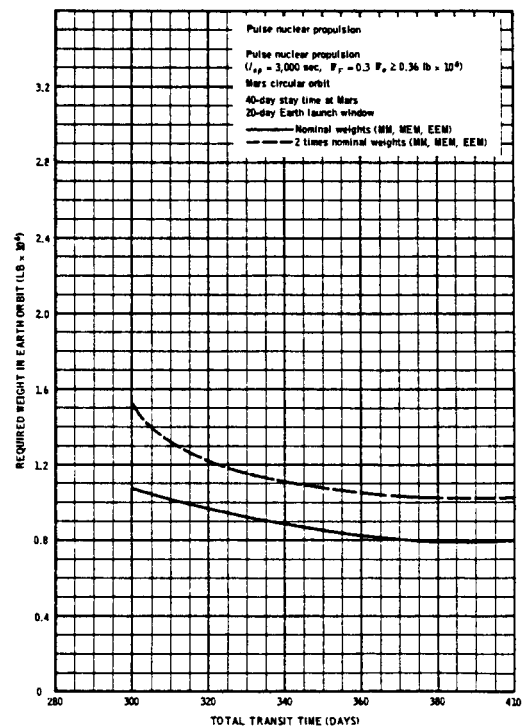


Figure B-7. Required Weight in Earth Orbit for Manned Mars Landing Mission in 1979-1980

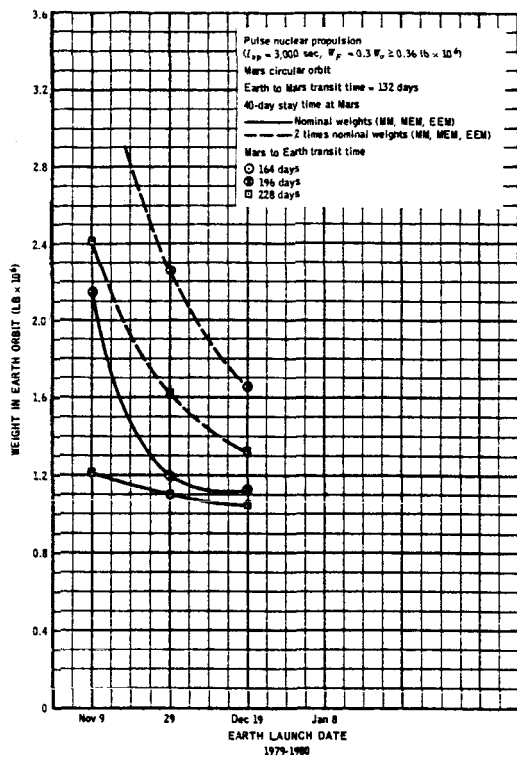


Figure B-8. Weight in Earth Orbit for Manned Mars Landing Mission in 1979-1980
 Earth to Mars Transit Time = 132 Days
 (Parabolic Earth Entry)

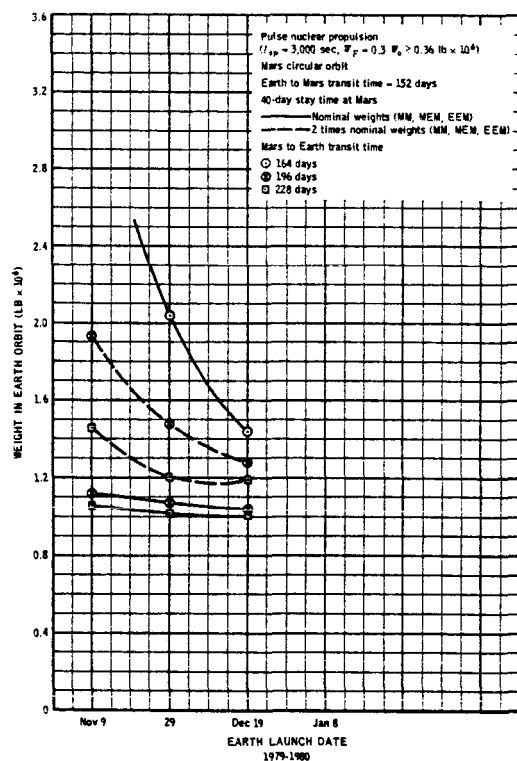


Figure B-9. Weight in Earth Orbit for Manned Mars Landing Mission in 1979-1980
 Earth to Mars Transit Time = 152 Days
 (Parabolic Earth Entry)

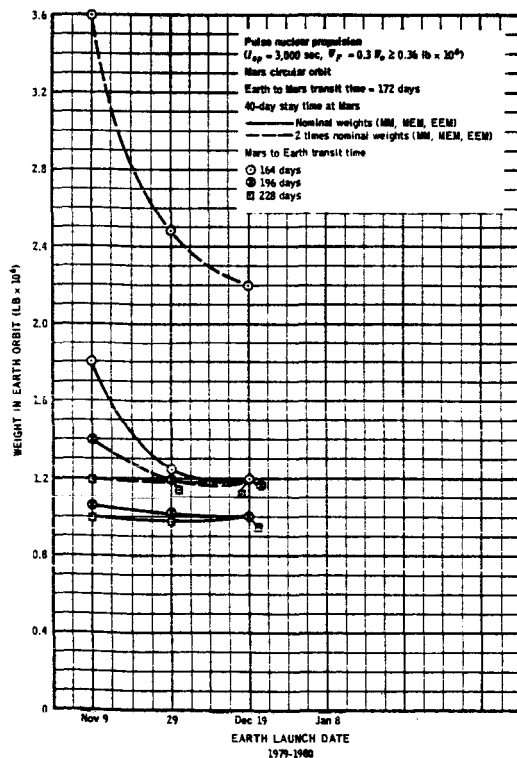


Figure B-10. Weight in Earth Orbit for Manned Mars Landing Mission in 1979-1980
 Earth to Mars Transit Time = 172 Days
 (Parabolic Earth Entry)

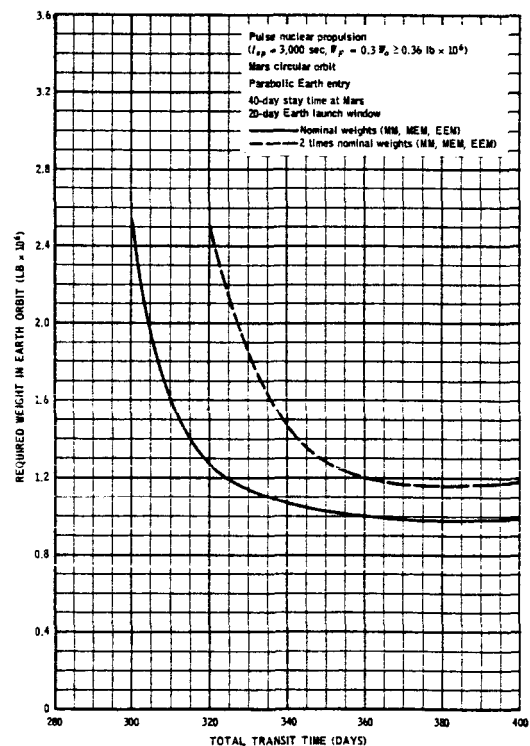


Figure B-11. Required Weight in Earth Orbit for Manned Mars Landing Mission in 1979-1980
 (Parabolic Earth Entry)

A comparison of the performance of the single-stage gaseous-core nuclear and pulse-nuclear propulsion systems with staged second-generation solid-core nuclear propulsion systems is shown in Figure B-12 for twice-nominal payload module weights and superparabolic Earth entry velocities. Staging of the gaseous-core and pulse-nuclear systems does not significantly change their performance because of the high system dead weights. It is obvious that for the lower-energy mission, 400-day total transit time, the required weight in Earth orbit is approximately the same using the gaseous-core and pulse-nuclear systems as it is using the second-generation solid-core nuclear propulsion systems. Only at short transit times, characteristic of higher-energy missions, do the gaseous-core and pulse-nuclear systems exhibit performance superior to that of staged solid-core systems. These performance estimates assume superparabolic entry; if high entry velocities at Earth cannot be used because of heating or high g levels, the gaseous-core and pulse-nuclear systems^a would show more substantial improvement over the solid-core system.

Figure B-13 presents a comparison of the performance of gaseous-core, pulse-nuclear, and fusion propulsion systems. All systems are constrained to enter at Earth with parabolic velocity and utilize twice-nominal payload module weights and a Mars circular orbit rendezvous profile. For this condition, use of the pulse-nuclear system decreases the required weight in Earth orbit by approximately a factor of 2 from that required using a gaseous-core nuclear propulsion system for flight times greater than 340 days. However, use of the fusion propulsion system decreases the required weight in Earth orbit by a factor of 2 from that required using the pulse-nuclear systems,^a and the fusion system is much less sensitive to total transit time.

^aThe pulse nuclear system performance was calculated for a fixed engine specific impulse. As discussed under growth potential, the attainable engine specific impulse increases with the initial weight of the spacecraft; therefore, the performance of the pulse-nuclear system would actually be better than indicated at the short transit times.

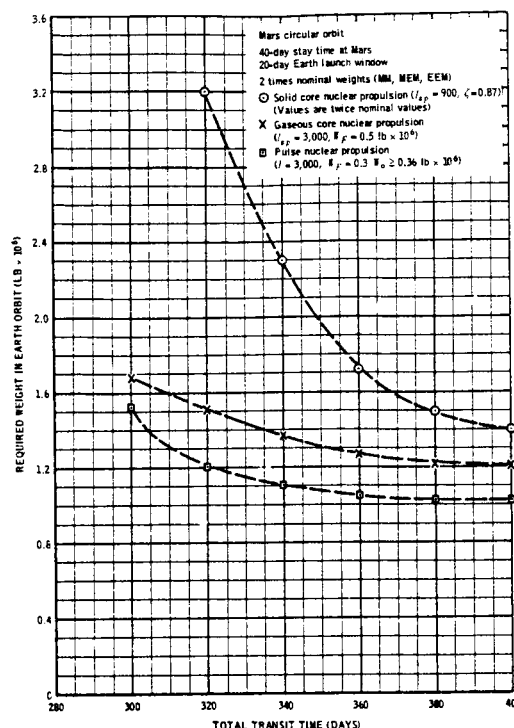


Figure B-12. Comparison Curves of Required Weight in Earth Orbit for Manned Mars Landing Mission in 1979-1980

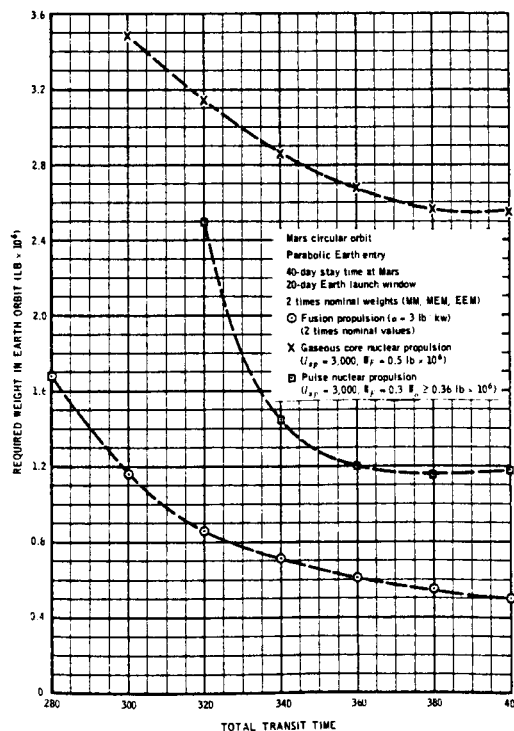


Figure B-13. Comparison Curves of Required Weight in Earth Orbit for Manned Mars Landing Mission in 1979-1980 (Parabolic Earth Entry)

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